Renewable and Sustainable Energy Reviews 41 (2015) 308–318

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A comparative assessment of Brazilian electric motors performance with minimum efficiency standards

Ildo L. Sauer [a,b], Hédio Tatizawa [a,b,*], Francisco A.M. Salotti [b], Sonia S. Mercedes [a,b]

[a] Energy Graduate Program, University of São Paulo (PPGE-USP), Brazil
[b] Institute of Energy and Environment, University of São Paulo (IEE-USP), Av. Prof. Luciano Gualberto, 1289 – São Paulo, SP, CEP 05508-010, Brazil

ARTICLE INFO

Article history:
Received 1 November 2013
Received in revised form
30 July 2014
Accepted 17 August 2014

Keywords:
Induction motors
High-efficiency motors
Energy saving
Energy-efficient motors
Energy efficiency
Labeling

ABSTRACT

The industrial electric motor is the most important load, considering its large number and associated energy consumption, being responsible for approximately 68% of the industrial energy consumption and 35% of the total electrical energy consumption in Brazil. This country, like others, is seeking to establish a regulation on the minimum efficiency index for electric motor equipment. This paper aims to present an overview of the installed park of industrial motors in Brazil and to evaluate the possible effects of such regulation. For this purpose, the measurement results obtained in the 2000–2012 period were used, which were extracted from the approximately 276 three-phase induction motors that had been sold and were being used in the Brazilian market, with a rated power in a large range from under 1 hp to over 150 hp. The analysis of the measurement results provided an overview of the average behavior of the induction motors in industry while considering energy efficiency and allowing estimates and proposals aiming at the improvement of the use of electrical energy.

Contents

1. Introduction

Electrical energy consumption in Brazil is rising, as is the economic growth in the last years, as shown in Fig. 1. In the last 13 years, electricity consumption has increased by a yearly average of 4.88%, reducing the growth of the GDP over the same period.

Hydroelectric power generation corresponds to approximately 435.5 TWh, or 82% of the total amount of energy generated (2011), as shown in Fig. 2.

The predominance of renewable hydroelectric energy sources, despite the environmental advantages of lower GHG emissions, is associated with a risk of supply problems due to the unpredictability of the weather because hydroelectric generation depends on the water supply of the large reservoirs on which is based the Brazilian electrical system. In recent years, the increase in electricity consumption also contributes to supply problems, e.g., in 2001–2002, when an exceptionally dry season led to a compulsory mobilization of the population to cut their electricity consumption by 25% on average. This campaign resulted in a significant consumption decrease, demonstrating that measures to change consumption habits can have a significant effect on the total electricity consumption.

* Corresponding author at: Energy Graduate Program, University of São Paulo (PPGE-USP), Brazil. Tel.: +55 11 30912574; fax: +55 11 38129251.
E-mail address: hedio@iee.usp.br (H. Tatizawa).

http://dx.doi.org/10.1016/j.rser.2014.08.053
1364-0321/

Nomenclature

ABNT Brazilian National Association of Technical Standards
CEMEP European Committee of Manufacturers of Electrical Machines and Power Electronics
cv Cheval-vapor = 0.9863 hp = 0.736 kW
EISA Energy Independence and Security Act (USA), 2007
EFF3, EFF2 and EFF1 efficiency levels for induction motors (EFF3 is the lowest, EFF1 is the highest), according to CEMEP
EPAct Energy Policy Act (USA), 1992
EU European Union
GDP Gross domestic product
GHG Green house gases
GWh 10^9 W h
hp horse-power
IEC International Electrotechnical Commission
IEEUSP Institute of Energy and Environment, of University of São Paulo
IEEE Institute of Electrical and Electronics Engineers
IE1, IE2 and IE3 efficiency levels for induction motors (IE1 is the lowest, IE3 is the highest), according to IEC 60034-30 Standard (2008)
NBR common denomination of ABNT standards
NEMA National Electrical Manufactures Association (USA)
NEMA Premium efficiency level for induction motor, according to NEMA
MWh 10^6 W h
SAE Society of Automotive Engineers
TWh 10^{12} W h
VSD variable speed drive, an electronic power supply for induction motors, with variable frequency

2. The electricity consumption profile in Brazil

The electrical motor is the most important load due to its large number and the associated electricity consumption, as described in Table 1, where an estimate of the typical electrical motor usage in the world is presented.

Fig. 3 presents an estimate of the electricity consumption in motors in selected countries.

Fig. 4 shows the sectors of the consumption of electricity in Brazil, and Fig. 6 shows the consumption in the industrial sector alone. As an estimate, there are 12 million motors in operation in the Brazilian industry [6]. According to Fig. 5, three-phase induction electrical motors account for 68% of the industrial consumption, primarily for moving pumps, fans and compressors, as shown in Fig. 6.

Thus, motors are responsible for 35% of the electrical energy consumption in Brazil, making their use a natural target for public policies aimed at enhancing energy efficient usage. Similar to both the European Union [8], and the USA [9], and others alike [5], Brazil is seeking to regulate the minimum energy efficiency indices for that equipment.

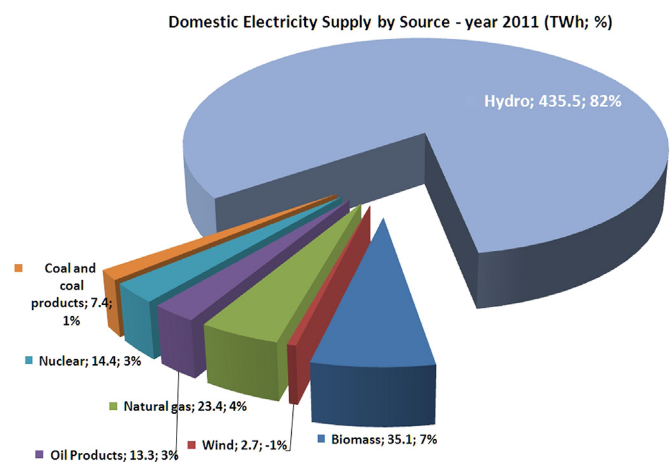

Fig. 2. Electricity generation in Brazil in 2011: total = 531.8 TWh. Adapted from [3].

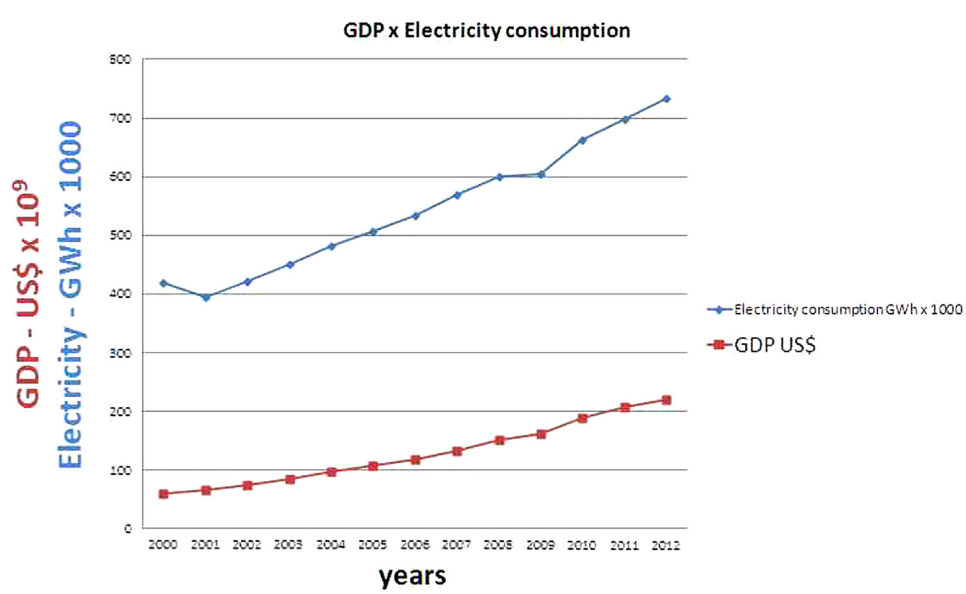

Fig. 1. Evolution of both electricity consumption and GDP in Brazil in recent years. Adapted from [1,2].

Table 1
Estimate of electrical motors usage, in the world.
Adapted from [4].

Motors of 10–750 W	Motors of 0.75–375 kW	Motors of 375–10,000 kW
Usage: small pumps, fans Monophasic Voltage: < 240 V Monophasic, induction type, usually built in other equipments and machinery Consumption of 9% of electricity Amount: 2 billion	Usage: pumps, fans, compressors, conveyors (industrial processes) Poliphasic Voltage: 200–1000 V Asynchronous, alternating current, induction, 2- 4- 6 or 8 poles, manufactured in production lines, standard type Consumption of 68% of electricity Amount: 230 million	Usage: in industry and infrastructure sector Poliphasic Voltage: 1–20 kV Synchronous, special design, produced on demand, assembled in site Consumption of 23% of electricity Amount: 0.6 million

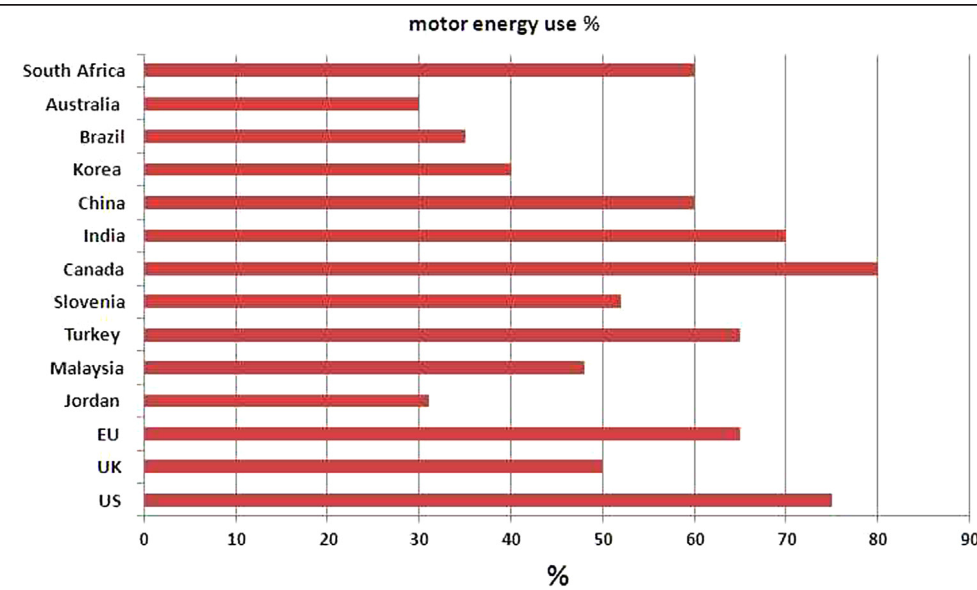

Fig. 3. Electricity consumption in motors in selected countries.
Adapted from [5].

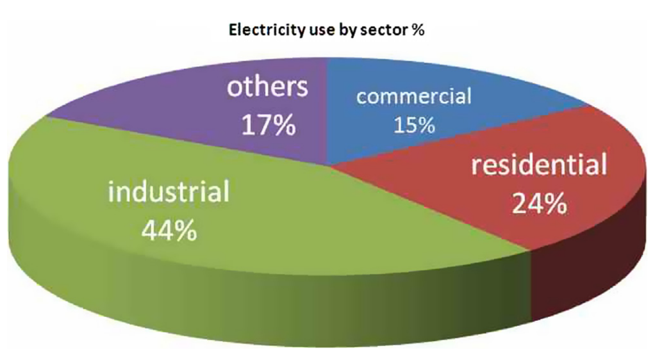

Fig. 4. Sectors of electricity consumption in Brazil (in 2011) [7].

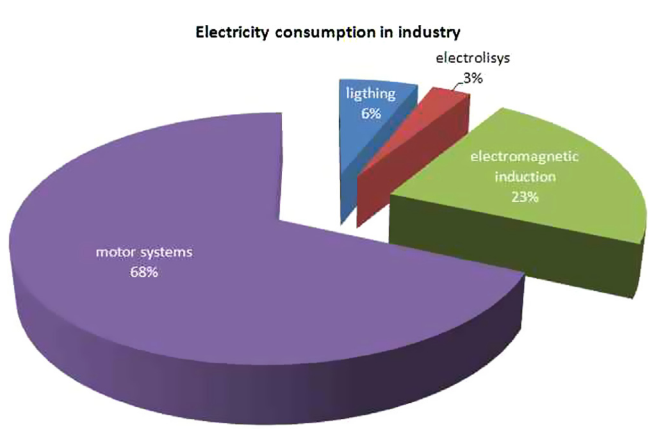

Fig. 5. Distribution of industrial electricity consumption [7].

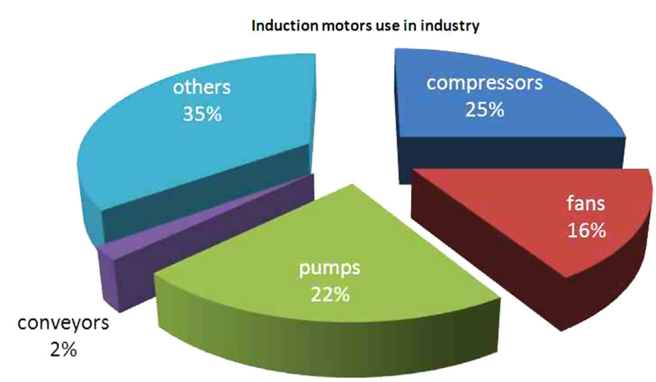

Fig. 6. Motor application in industry, according to end use [6].

Table 2
Trade of three phase squirrel cage motors between USA and Brazil (rated power 750 W–75 kW) [13] (1 US$=R$ 2.00).

Year	Export (to USA)		Import (from USA)	
	US$ FOB	Amount	US$ FOB	Amount
2007	53,117,987	202,153	1,474,793	514
2008	63,303,856	234,068	1,259,193	1231
2009	38,423,279	145,536	1,268,425	508
2010	77,114,900	269,602	785,226	457
2011	103,523,617	289,739	438,805	126
2012 (up to August)	83,056,133	195,777	1,448,344	973

Table 3
Trade of three phase squirrel cage motors between European Union (EU) and Brazil (rated power 750 W–75 kW) [13]. (1 US$=R$ 2.00).

Year	Export (to EU)		Import (from EU)	
	US$ FOB	Amount	US$ FOB	Amount
2007	73,416,098	297,771	7,393,719	18,682
2008	81,739,163	297,126	10,778,849	38,839
2009	39,408,048	146,264	7,967,999	38,209
2010	52,376,887	217,261	7,980,525	38,420
2011	97,432,522	305,710	9,264,608	38,897
2012 (up to August)	62,853,324	181,669	6,025,519	19,947

Table 4
Efficiency levels of Regulation EU 640/2009 [a], [b] [10].

Power kW	Nominal minimum efficiencies (η) for IE2 efficiency level (50 Hz)			Nominal minimum efficiencies (η) for IE3 efficiency level (50 Hz)		
	2	4	6	2	4	6
0.75	77.4	79.6	75.9	80.7	82.5	78.9
1.1	79.6	81.4	78.1	82.7	84.1	81
1.5	81.3	82.8	79.8	84.2	85.3	82.5
2.2	83.2	84.3	81.8	85.9	86.7	84.3
3	84.6	85.5	83.3	87.1	87.7	85.6
4	85.8	86.6	84.6	88.1	88.6	86.8
5.5	87	87.7	86	89.2	89.6	88
7.5	88.1	88.7	87.2	90.1	90.4	89.1
11	89.4	89.8	88.7	91.2	91.4	90.3
15	90.3	90.6	89.7	91.9	92.1	91.2
18.5	90.9	91.2	90.4	92.4	92.6	91.7
22	91.3	91.6	90.9	92.7	93	92.2
30	92	92.3	91.7	93.3	93.6	92.9
37	92.5	92.7	92.2	93.7	93.9	93.3
45	92.9	93.1	92.7	94	94.2	93.7
55	93.2	93.5	93.1	94.3	94.6	94.1
75	93.8	94	93.7	94.7	95	94.6
90	94.1	94.2	94	95	95.2	94.9
110	94.3	94.5	94.3	95.2	95.4	95.1
132	94.6	94.7	94.6	95.4	95.6	95.4
160	94.8	94.9	94.8	95.6	95.8	95.6
200 Up to 375	95	95.1	95	95.8	96	95.8

Notes to Table 4:

[a] IE2 levels are equivalent to EFF1 levels from voluntary agreement between CEMEP/EU.

[b] IE3 levels are equivalent to Nema Premium level from the USA's Energy Independence and Security Act, 2007 [12].

3. The Brazilian induction motor market and its regulation

It is generally accepted that regulatory measures can shape the market of induction motors [10–12]. The induction motor industry in Brazil is also strongly affected by the needs of the export market, primarily the US and the European Union. As shown in Tables 2 and 3, trade with these two markets is dominated by three-phase squirrel cage motors with rated powers ranging from 750 W to 75 kW.

Consequently, the international trade of motors manufactured in Brazil affects the efforts of the Brazilian industry in producing more efficient products, aiming at improved acceptance by the export markets, particularly the markets with a more stringent regulation concerning efficiency. Additionally, the regulation focused on the possible effects of energy efficiency practices in the importing countries on the energy efficiency performance of the motors manufactured in Brazil.

The initial steps towards implementation of an energy efficiency regulation in the EU started in 1998, through the CEMEP (European Committee of Manufacturers of Electrical Machines and Power Electronics) [14], where a voluntary agreement was settled, and the efficiency levels EFF3, EFF2 and EFF1 were defined (EFF3 being the lowest, and EFF1 being the highest). By 2009, this commission approved Regulation no. 640/2009 [8]. A major change in this regulation was the adoption of the efficiency levels defined by the international standard IEC 60034-30–2008 [15]: IE1 for Standard Efficiency; IE2 for High Efficiency; and IE3 for Premium Efficiency.

According to Regulation no. 640/2009 (2009) [8], since June 16, 2011, motors are not allowed to be less efficient than the IE2 level (see Table 4). By January 2015, motors with rated power ranging from 7.5 kW to 375 kW shall comply with the IE3 level or be equipped with a VSD (variable speed drive) and comply with the IE2 level, according to Table 4. Furthermore, by January 2017, motors with rated power ranging from 0.75 kW to 375 kW shall comply with the IE3 level or be equipped with a VSD and comply with the IE2 level, according to Table 4.

Table 4 presents the Regulation EU 640/2009 efficiency levels, which are valid for three-phase motors rated from 0.75 kW to 375 kW.

The 80s was a period of slow economic growth, and in the U.S. in 1987, NEMA published the MG1-12-6B standard, which served as a model for the MG1-12-6C standard that was published three years later, with a revised edition published in 2011 [16]. In 1992, the Energy Policy Act (EPAct) [9] was published by the U.S. Congress, with the first Law presenting the minimum efficiency levels for induction squirrel cage motors, for general use, single speed, 230–460 V, 1–200 hp, 2–6 poles. This definition applies to motors used in industry in general. The mandated rated efficiencies are 1–4% better than the previous standard motors they replaced. The EPAct came into force in 1997. Aiming to achieve even better efficiency levels, the EPAct was renewed in 2005, making compulsory the use of NEMA Premium motors in government buildings. In 2007, the publication by the Congress of the Energy Independence and Security Act (EISA) [17] mandated that all types of motors described in the EPAct should comply with the NEMA Premium level (see Table 5) by December, 2010. EISA has broadened the universe of regulated motors and has also specified a schedule for the market transition.

Like others countries [5,18], a labeling program has been carried out in Brazil covering about 40 groups of electrical appliances and equipment, and is mandatory for induction motors since 2010. In this country, the compulsory regulation of the efficiency of induction motors evolved in two steps, initially with Decree no. 4.508/2002 [19], in which three-phase induction motors, squirrel cage rotor, rated voltage up to 600 V, rated power ranging from 1 cv up to 250 cv, number of poles of 2, 4, 6 and 8, were included. In this regulation, two classes of motors were defined: Standard and High Efficiency motors. This regulation covers approximately 80% of the Brazilian market.

Table 6 shows the minimum efficiency values defined by decree 4.508/2002 for Standard and High efficiency motors [19].

Step two of the regulation of induction motors in Brazil was set by Ordinance 553, of 2005 [20], in which reference values for the efficiency of induction motors were taken from Table 6 but retained only the high efficiency values (right side of Table 6). This ordinance was gradually implemented, and only high-efficiency motors have been allowed in the Brazilian market since 2010.

4. Evaluation of the performance of three-phase induction motors in Brazil, according to efficiency

Considering the scenario presented in the previous section, this paper intends to provide an overview of the installed park in

Table 5
Efficiency levels of EISA subtype I motors (60 Hz) [14].

Full-load efficiencies for 60 Hz Nema Premium® efficiency electric motors				Full-load efficiencies for 60 Hz Nema Premium® efficiency electric motors			
Rated 600 V or less (random wound)				Rated 600 V or less (random wound)			
Open motors				Enclosed motors			
hp	2 Pole Nominal efficiency	4 Pole Nominal efficiency	6 Pole Nominal efficiency	hp	2 Pole Nominal efficiency	4 Pole Nominal efficiency	6 Pole Nominal efficiency
1	77	85.5	82.5	1	77	85.5	82.5
1.5	84	86.5	86.5	1.5	84	86.5	87.5
2	85.5	86.5	87.5	2	85.5	86.5	88.5
3	85.5	89.5	88.5	3	86.5	89.5	89.5
5	86.5	89.5	89.5	5	88.5	89.5	89.5
7.5	88.5	91	90.2	7.5	89.5	91.7	91
10	89.5	91.7	91.7	10	90.2	91.7	91
15	90.2	93	91.7	15	91	92.4	91.7
20	91	93	92.4	20	91	93	91.7
25	91.7	93.6	93	25	91.7	93.6	93
30	91.7	94.1	93.6	30	91.7	93.6	93
40	92.4	94.1	94.1	40	92.4	94.1	94.1
50	93	94.5	94.1	50	93	94.5	94.1
60	93.6	95	94.5	60	93.6	95	94.5
75	93.6	95	94.5	75	93.6	95.4	94.5
100	93.6	95.4	95	100	94.1	95.4	95
125	94.1	95.4	95	125	95	95.4	95
150	94.1	95.8	95.4	150	95	95.8	95.8
200	95	95.8	95.4	200	95.4	96.2	95.8

Table 6
Minimum efficiency values defined by decree 4.508/2002 [15].

		Standard				High efficiency			
cv or hp	kW	2	4	6	8	2	4	6	8
1	0.75	77	78	73	66	80	80.5	80	70
1.5	1.1	78.5	79	75	73.5	82.5	81.5	77	77
2	1.5	81	81.5	77	77	83.5	84	83	82.5
3	2.2	81.5	83	78.5	78	85	85	83	84
4	3	82.5	83	81	79	85	86	85	84.5
5	3.7	84.5	85	83.5	80	87.5	87.5	87.5	85.5
6	4.5	85	85.5	84	82	88	88.5	87.5	85.5
7.5	5.5	86	87	85	84	88.5	89.5	88	85.5
10	7.5	87.5	87.5	86	85	89.5	89.5	88.5	88.5
12.5	9.2	87.5	87.5	87.5	86	89.5	90	88.5	88.5
15	11	87.5	88.5	89	87.5	90.2	91	90.2	88.5
20	15	88.5	89.5	89.5	88.5	90.2	91	90.2	89.5
25	18.5	89.5	90.5	90.2	88.5	91	92.4	91.7	89.5
30	22	89.5	91	91	90.2	91	92.4	91.7	91
40	30	90.2	91.7	91.7	90.2	91.7	93	93	91
50	37	91.5	92.4	91.7	91	92.4	93	93	91.7
60	45	91.7	93	91.7	91	93	93.6	93.6	91.7
75	55	92.4	93	92.1	91.5	93	94.1	93.6	93
100	75	93	93.2	93	92	93.6	94.5	94.1	93
125	90	93	93.2	93	92.5	94.5	94.5	94.1	93.6
150	110	93	93.5	94.1	92.5	94.5	95	95	93.6
175	132	93.5	94.1	94.1		94.7	95	95	
200	150	94.1	94.5	94.1		95	95	95	
250	185	94.1	94.5			95.4	95		

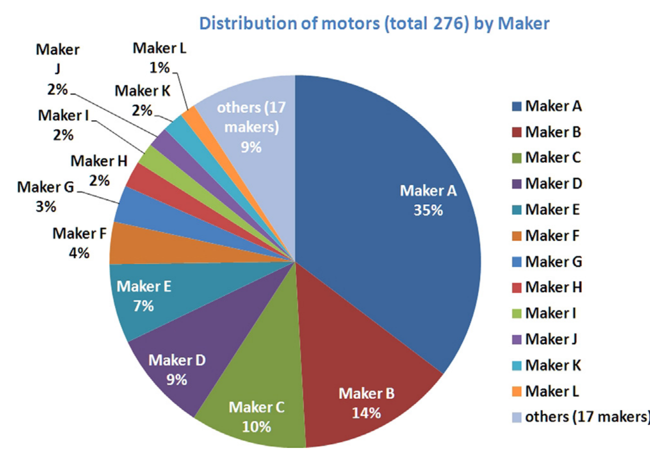

Fig. 7. Distribution of the motors analyzed in this research, by maker.

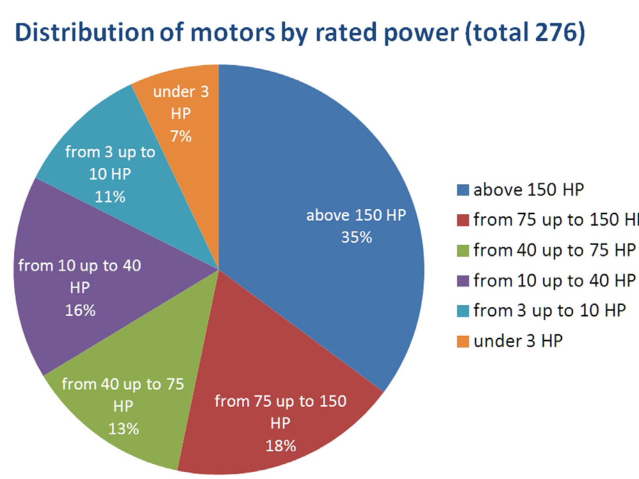

Fig. 8. Distribution of the motors analyzed in this research, by rated power.

industry in Brazil and to estimate the possible effects of the application of the efficiency regulation. For this purpose, test results of laboratory measurements on induction motors were used, which were performed in the 2000–2012 period on approximately 276 induction motors available in the Brazilian market from 29 different makers and with rated powers up to 250 hp. Those results were available on the laboratory's records and came from the main manufacturers and users. The efficiency results were obtained by means of test procedures widely accepted by the industry, and were based on Brazilian standard NBR 5383/1:1999, method 2 [21], which

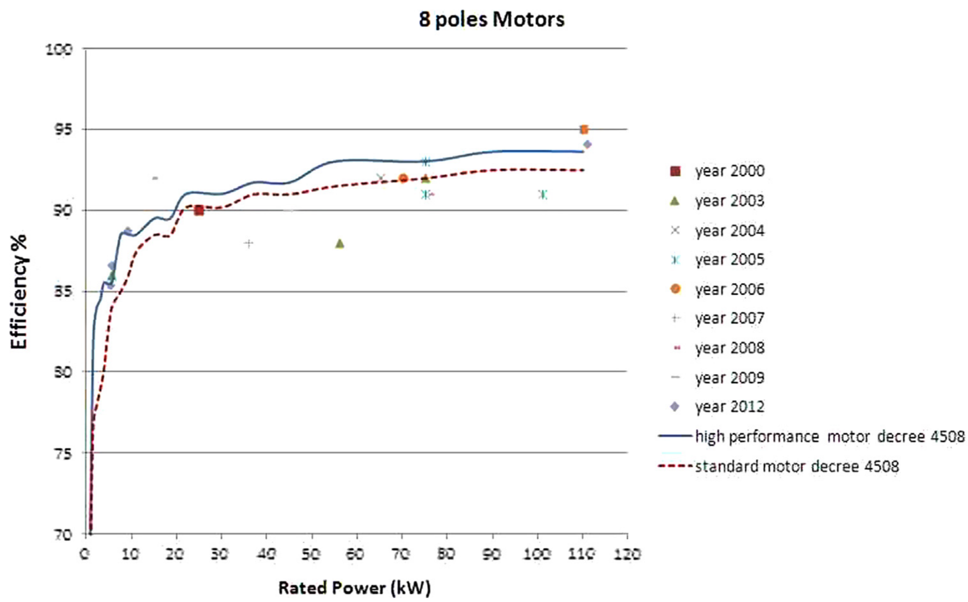

Fig. 9. Measurements of the efficiency of 8-pole induction motors compared with the minimum values of efficiency for standard and high-efficiency motors according to the Brazilian regulation decree 4508/2002 [19].

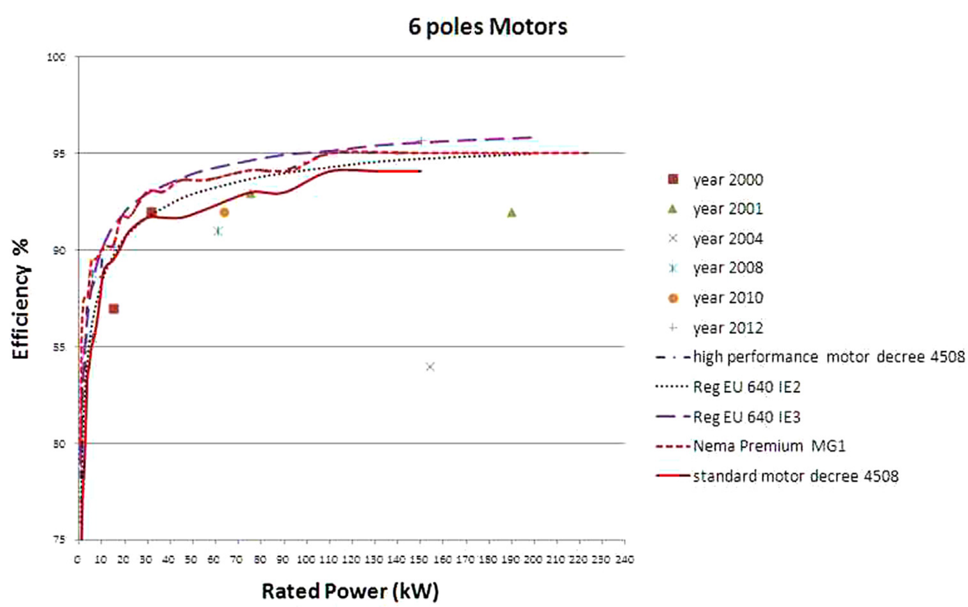

Fig. 10. Measurements of the efficiency of 6-pole induction motors compared with the efficiency levels IE2 and IE3 of regulation EU 640 [8] from the European Union, the Premium efficiency level from the NEMA MG1 standard [16], and the minimum values according to Brazilian Decree 4508/2002 [19].

is similar to standard IEEE – 112:1991 – method B [22]. This method, according to standard IEC 60034-2-1/2007 [23], leads to the lowest uncertainties results for efficiency measurements. In Figs. 7 and 8 are presented the distribution of the motors analyzed in this research, sorted by maker (identified with letters from A to L) and by rated power (grouped in 6 ranges). All the tests were performed in the Electrical Machines Laboratory of Institute of Energy and Environment at the University of São Paulo – IEEUSP [24]. This Institute has performed certified tests in equipment for industry since 1912. The electrical machines laboratory where tests were performed is an accredited laboratory by INMETRO [25], which is the Brazilian federal organism for metrology, standardization and industrial quality. The accreditation process of this laboratory is ruled by the international standard ISO/IEC 17025 [26], and by International Laboratory Accreditation Cooperation (ILAC) [27].

The efficiency tests in the induction motors were performed according to Brazilian standard NBR 5383/1:1999, method 2 [21]. This method is similar to standard IEEE – 112:1991 – method B [22], and it is performed using a dynamometer, with indirect measurement of the supplemental losses and direct measurement for the losses in the stator (I^2R), rotor (I^2R), and the iron core, as well as the losses due to friction and ventilation. In this method, the input and output power are measured, and the apparent losses are calculated by subtracting one from another. The supplemental losses are calculated by subtracting from the apparent losses the remaining loss components, which in turn is obtained by direct measurement of the I^2R losses in the stator and rotor, the iron core losses and the losses by friction and ventilation.

The induction motors tested in this research provide a picture of the installed park in Brazilian industry, and they belong to a set

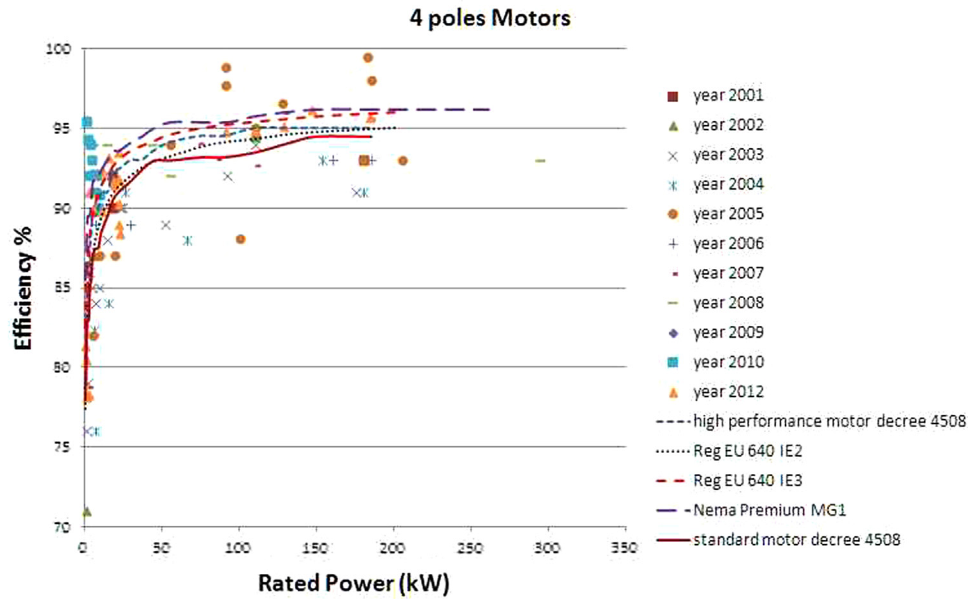

Fig. 11. Measurements of the efficiency of 4-pole induction motors compared with the efficiency levels IE2 and IE3 of regulation EU 640 [8] from the European Union, the Premium efficiency level from the NEMA MG1 standard [16], and the minimum values according to Brazilian Decree 4508/2002 [19].

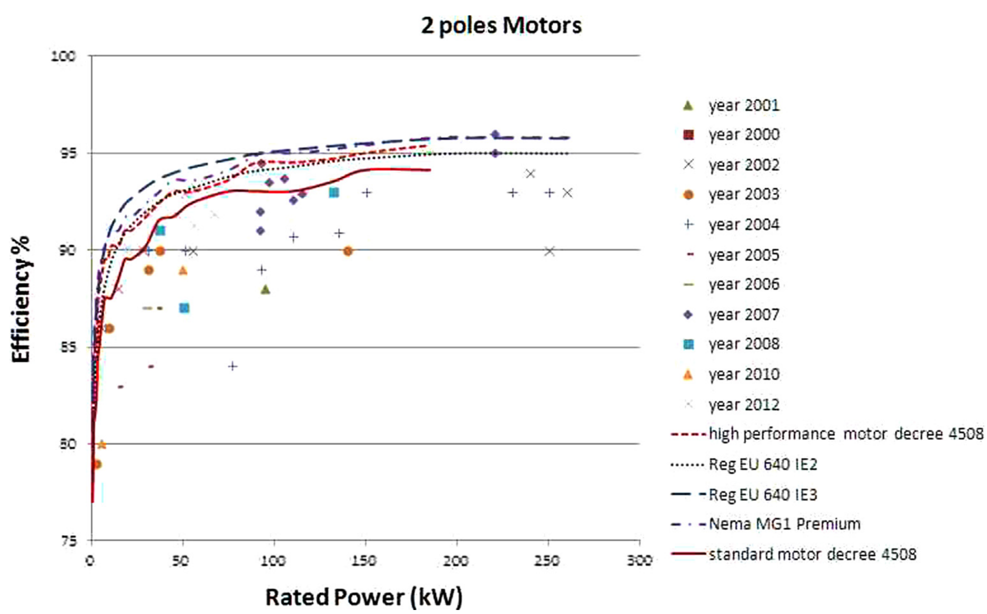

Fig. 12. Measurements of the efficiency of 2-pole induction motors compared with the efficiency levels IE2 and IE3 of regulation EU 640 [8] from the European Union, the Premium efficiency level from the NEMA MG1 standard [16], and the minimum values according to Brazilian Decree 4508/2002 [19].

of industries ranging from small size up to large size, representing rated powers ranging from low to high.

Fig. 9 shows the results of the measurements performed in 8-pole induction motors compared with the minimum values of efficiency of the Brazilian regulation decree 4508/2002 [19] for standard and high-efficiency motors. Those 8-pole motors are neither covered by the European Union regulation EU 640 [8], nor the US standard NEMA MG1 [16].

Fig. 10 shows the efficiency measurement results for 6-pole motors compared with the efficiency levels IE2 and IE3 of regulation EU 640 [8], from the European Union, the Premium efficiency level from the NEMA MG1 standard [16], and the minimum values according to Brazilian Decree 4508/2002 [19].

Fig. 11 shows the results of the efficiency measurements for 4-pole motors, which are the most widely used in industry, compared with the efficiency levels IE2 and IE3 of regulation EU 640 [8] from the European Union, the Premium efficiency level from the NEMA MG1 standard [16], and the minimum values according to Brazilian Decree 4508/2002 [19].

Fig. 12 shows the results of the efficiency measurements of 2-pole motors compared with the efficiency levels IE2 and IE3 of regulation EU 640 [8] from the European Union, the Premium efficiency level from the NEMA MG1 standard [16], and the minimum values according to Brazilian Decree 4508/2002 [19].

From Figs. 9–12, nearly all the motors subjected to the tests exhibit efficiency levels below the ones from Brazilian decree 4508/2002 [19]; in addition, these motors comply with neither the indices of US NEMA MG1 Premium level [16] nor the European Union efficiency levels from regulation EU 640 [8].

Figs. 13–16 show the absolute deviations between the measured values and the values from decree 4508/2002 [19] for 8-, 6-, 4- and 2-pole motors. Negative values indicate that the efficiency

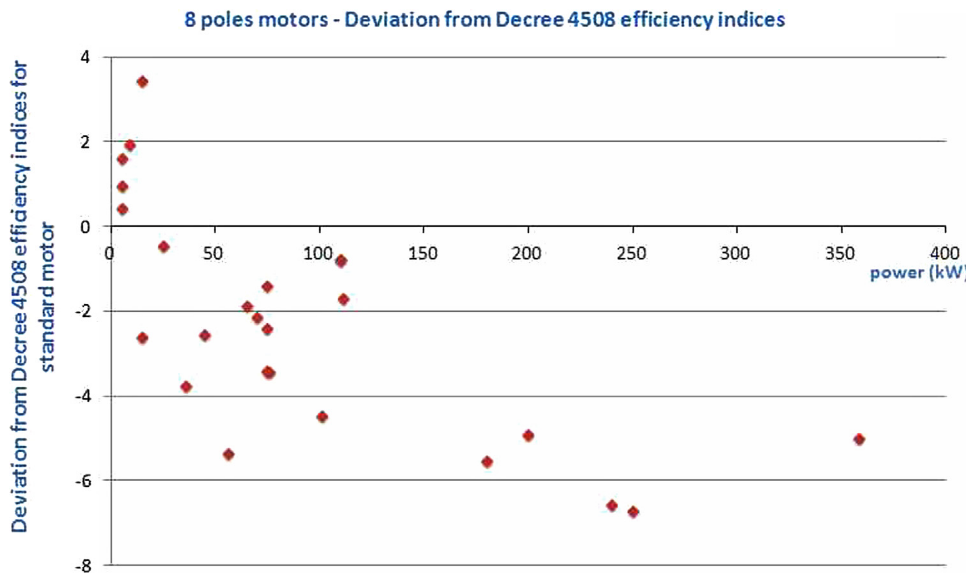

Fig. 13. Absolute deviations between the values of the efficiency measurements and the values from decree 4508/2002 [19], according to the rated powers of the motors, for 8-pole motors. Negative values indicate that the efficiency of this type of motor is below the foreseen efficiency level of the regulation.

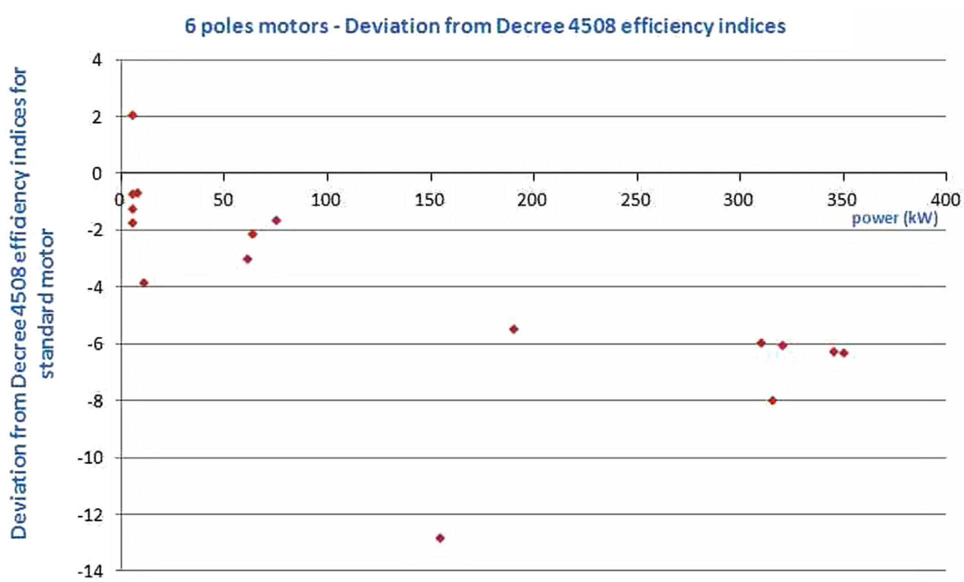

Fig. 14. Absolute deviations between the values of the efficiency measurements and the values from decree 4508/2002 [19], according to the rated powers of the motors, for 6-pole motors. Negative values indicate that the efficiency of this type of motor is below the foreseen efficiency level of the regulation.

of this motor is below the efficiency level foreseen by this regulation, considering the rated powers of the motors.

Table 7 summarizes the results presented in Figs. 13–16, indicating the average of the deviation of the foreseen minimum efficiency values of decree 4508/2002 [19], and the standard deviation, median values, maximum deviations (positive and negative) for 8-, 6-, 4- and 2-pole motors.

At first glance, the analysis of the mean and the median values shown in Table 7 can lead to a mistaken conclusion that the measured efficiencies are close to the foreseen values of decree 4508/2002 [19]. However, the high values of the standard deviation indicate the high scatter of those deviations from the regulation, as can also be seen, qualitatively, by visual inspection of Figs. 13–16.

This paper intends to present a comparison of the performance of induction motors concerning energy efficiency, performed under 100% loading, with efficiency minimum values of the Brazilian regulation decree 4508/2002 [19] and those presented by the European Union regulation EU 640 [8], and the US standard NEMA MG1 [16]. Considering that the efficiency results were obtained in the laboratory under ideal conditions, and with 100% loading, it is expected that the behavior of the machines installed in the industry, where ideal conditions are not present, will show worst results than the ones presented in the paper, and so, supporting the great importance of compulsory regulation of induction motors. Also, on authors' perception, the motors of this sample belong to a selected set, presenting a better performance than the country's average, because they came from the main manufacturers and users, and under this perception, showing a greater concern on the overall quality of the motors, including energy efficiency, and prone to know and to expose to disclosure the performance of their machines, by performing laboratory tests in an accredited laboratory, regardless of the associated costs. The high dispersion of the deviation values indicates great variability between the induction motors of same rated characteristics, but from different makers. The above results highlight the need for the

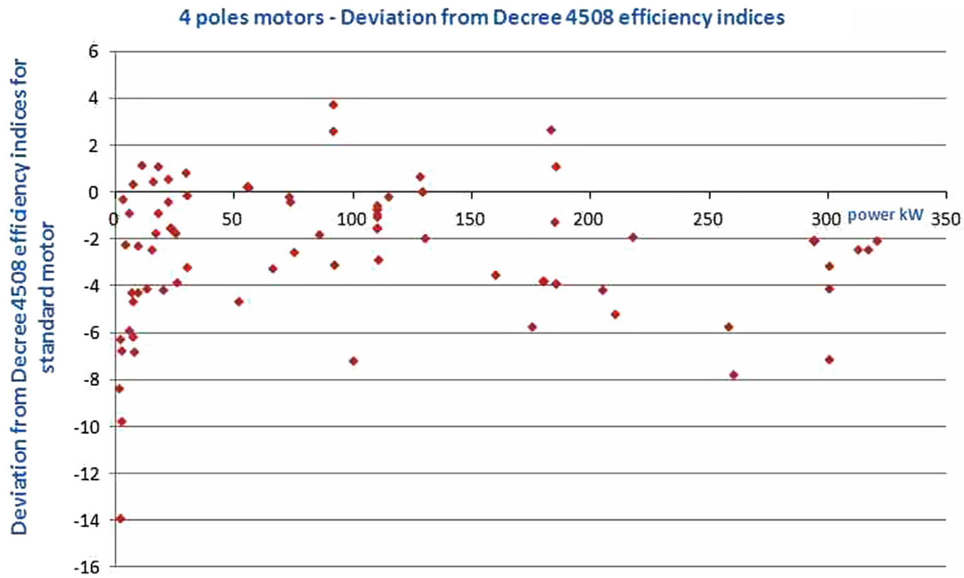

Fig. 15. Absolute deviations between the values of the efficiency measurements and the values from decree 4508/2002 [19], according to the rated powers of the motors, for 4-pole motors. Negative values indicate that the efficiency of this type of motor is below the foreseen efficiency level of the regulation.

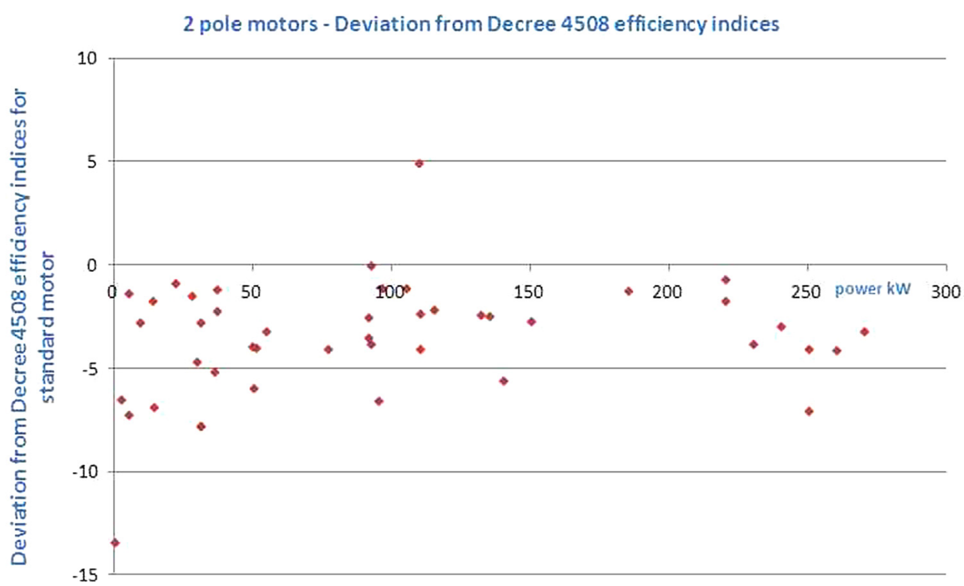

Fig. 16. Absolute deviations between the values of the efficiency measurements and the values from decree 4508/2002 [19], according to the rated powers of the motors, for 2-pole motors. Negative values indicate that the efficiency of this type of motor is below the foreseen efficiency level of this regulation.

Table 7
Deviation from minimum efficiency values foreseen in decree 4508/2002 [15].

No. of poles	Average deviation %	Standard deviation	Median value	Highest deviation (−)	Highest deviation (+)
2 Poles	−3.54	2.83	−3.20	−13.43	4.95
4 Poles	−2.47	2.78	−2.07	−13.88	3.73
6 Poles	−3.98	3.61	−3.42	−12.81	2.06
8 Poles	−2.30	2.70	−2.40	−6.71	3.44

regulation of induction motors, considering their role as important loads for the electrical system. In Brazil, 12,000,000 induction motors are estimated to be installed in industry, with a yearly national sales volume of approximately 1,000,000 units [6]. Thus, the currently installed park will be replaced, in the short to medium term, by improved efficiency motors, considering the present regulatory framework, and the average lifetime of 15 years for a polyphase electric motor [10].

5. Energy efficiency improvement perspectives for induction motors in Brazil

The efficiency of induction motors can be increased by improvements in their design and in the material used in their manufacturing. A significant fraction of the losses (15–25%) in induction motors result from Eddy currents and hysteretic processes in the motor laminations. These so-called core losses depend on the magnetic field B intensity, on the quality of the steel, the steel thickness and the insulation between the sheets, so, efficiency improvement could include increase in core active volume, or decrease in field intensity [28,29]. High-efficiency motors have a higher volume of iron core, resulting in a decrease in the flux density, thereby leading to reduced iron losses. In general, three types of steel can be used: SAE 1006/1008, in 0.6-mm-thick sheets, with specific losses of 4 W/kg; the core type, with a thickness of 0.6 mm and losses of 2.5–4 W/kg; and silicon steel sheets, with a thickness of 0.5–0.23 mm and losses

Table 8
Test results of the samples, compared to the efficiency levels of Brazilian regulation Decree 4508/2002 [19].

Decree 4508	2 Poles	4 Poles	6 Poles	8 Poles	Total
Efficiency below minimum	98%	84%	94%	80%	89%
Efficiency above minimum	2%	16%	6%	20%	11%

of 1.3–2.5 W/kg. Mechanical losses caused by friction in the bearings and ventilation constitute 5–15% of the losses. Supplemental losses (15–25% of the total) are caused by poor distribution of the currents and magnetic flux, and the magnetic flux imperfections in the air gap of the motors [30–32]. High-efficiency motors cost more than standard motors. In Brazil, high-efficiency motors cost 40% more on average than standard motors [33]. A higher efficiency means lower electricity consumption, or a lower electricity bill, which can be a major factor for the replacement of standard motors in industry.

The measurement results indicate a high dispersion of the efficiency values for the motors subjected to the tests, considering Figs. 13–16. All the tests were performed in the laboratory under controlled conditions, with the motors under full load or under a rated mechanical load. Considering that induction motors exhibit higher efficiency under such controlled conditions, it is quite possible to conclude that under field conditions or in the industrial environment, these motors operate below the rated load [31,34,35], which, in turn, means that they operate with a lower efficiency than the figures obtained during the laboratory tests. Considering the high costs of electricity in Brazil, which is equivalent to US$ 160/MWh for industrial consumers, the replacement of standard motors working under low loads by high-efficiency motors working near the rated conditions is worthwhile, particularly when the motors operate under nearly continuous operation, for example, for 8000 h/year.

Consider the example of a 4-pole high efficiency motor with a rated voltage of 380 V and a rated power of 100 cv, which, in Brazil, costs the equivalent of US$ 4,000. Considering a working rate of 8000 h/year, by using this motor to replace a standard one with the same characteristics but operating under 80% of the rated load (and with an efficiency 5% lower) results in a payback term of 18 months [31]. In the case of motors operating under 75% of the rated load (considering operation of 8000 h/year), the replacement of the under-loaded motor by a high efficiency motor with a lower rated power (and smaller dimensions) should be made together with some mechanical adaptation in the coupling of the motor to the mechanical load. In that situation, the cost of such adaptations should be included in the economic analysis; however, in general, a short payback period is obtained, again considering the high cost of electricity in Brazil. The payback period can be shortened by considering the possible electricity bill decrease related to the power demand drop. In this analysis, the motors were not considered to be working under low loading and under a low power factor. Such an undesired situation, besides causing additional energy losses in the cables and wires by circulation of reactive power, may cause an additional increase in the electricity bill as long as the Brazilian regulation imposes penalties if the electrical installation operates with a power factor of under 0.92 [36]. This power factor problem can be addressed by installing power factor correction equipment, which leads to additional costs. However, the use of power factor correction is not free of drawbacks because the installation of power factor correction capacitors can increase problems with harmonic currents and harmonic voltages by creating resonant circuits tuned to the harmonic frequencies in the electrical installation, a common situation, which may cause additional energy losses, over-currents, over-voltages and equipment malfunction.

A fraction of the motors tested in this research may have been replaced in the industry since the tests dated from 2000 to 2012 because motors exhibit an average life of 12–15 years [10] and the sales volume is 1,000,000 units/year in Brazil [6]. However, it is expected that a significant fraction of the motors are still in operation, primarily those motors with higher rated power because it is a common practice in industry to perform maintenance and refurbishment of the motor windings after motor failures have occurred. This procedure is also applied to smaller motors of rated powers of 0.75 kW and above. Such maintenance procedures, if performed improperly, result in motors of poorer-performance, decreasing efficiency in 1–5% [29,37], despite some approaches pointing an improvement using proper techniques in the rewinding process [38,39,29], but those techniques are not common in practice, in Brazil. The reasons for the adoption of such procedures could include a lower cost for the maintenance compared with the price of a new motor [40], often due to bureaucratic reasons because approval of a maintenance task generates less paperwork than does the purchase of a new motor, especially in public companies or in large-sized companies.

6. Conclusions and recommendations

The tests performed in the motors used in industry exhibited a varied or contrasting set of results concerning energy efficiency. In the majority of cases, efficiency indices far below the values of the Brazilian regulation for high-performance motors [19], the NEMA Premium level [16], or either the EU 640 IE2 or IE3 level [8] were obtained. In fact, as shown in Figs. 9–12, most of the motors installed in industry before the validity of Ordinance 553/553 [20], which took effect in 2010, did not comply with the standard motor level of decree 4508/2002, demonstrating that before the regulation, the waste of electricity in industry was quite high.

The set of 276 machines sent by the manufacturers and users for testing were, in most of the cases, single pieces. For statistical purposes, if each motor could have been considered as a sample with just one single piece, and adopting as a criterion of acceptance (pass or fail) the minimum level of efficiency of the Brazilian regulation Decree 4508/2002 [19], we could conclude that most of the samples would fail, as shown in Table 8.

The above figures suggest the poor performance of the machines, concerning efficiency.

Note that the test results apply to motors under 100% of the rated mechanical load, in which the efficiency is better. In practice, in an industrial environment, motors are often used under low loading or below their rated mechanical loading. In this situation, the efficiency levels are below those obtained during the laboratory tests. Considering the high cost of electricity in Brazil in general, it is worthwhile to replace those standard motors with high-efficiency ones if the motors operate for a large number of hours, i.e., near 8000 h/year. The replacement is also worthwhile if the motor operates with a loading of under 75%, in which case, the motor is replaced by a smaller one in both rated power and size. This replacement requires a mechanical adaptation in the industrial process. In both cases, an economic analysis must be performed; however, in general, a short payback is expected considering the high cost of electricity in Brazil.

As shown in Fig. 1, the economic growth in Brazil is developing in parallel with the electricity consumption, indicating that it is important to improve the efficiency in the use of the energy. Considering that induction motors use approximately 35% of the electricity consumed in Brazil, the results in this research demonstrate that the poor efficiency of the motors in industry highlights

the suitability of the public policies implemented regarding the regulation of the efficiency of motors.

The annual sales of 1,000,000 motors and a total deployment of 12,000,000 motors indicate that in the near future, this picture of the waste of energy related to induction motors will change because the sale of motors is now occurring in a regulated environment; however, such implementation of new motors should be complemented by campaigns to encourage the replacement of old motors and to discourage the common practice of the refurbishment of motors.

The adoption by the U.S. of the NEMA Premium levels for induction motors since 2010 and the future implementation of the IE3 level by the European Union by 2015 may have some effect in the Brazilian regulation by 2015 towards those goals.

References

[1] IBGE – Brazilian Institute of Geography and Statistics, ⟨http://www.ibge.gov.br/home/estatistica/indicadores/pib/defaultcnt.shtm⟩; 2013 [accessed 08.09.2013] [Portuguese].

[2] ONS – Brazilian National Electric Grid Operator, ⟨http://www.ons.org.br/historico/carga_propria_de_energia_out.aspx⟩; 2013 [accessed 08.09.13] [Portuguese].

[3] Brazil, Brazilian Ministry of Energy and Mining, ⟨https://ben.epe.gov.br/downloads/Relatorio_Final_BEN_2012.pdf⟩; 2013 [accessed 08.09.13] [Portuguese].

[4] Brunner C, Waide P. Energy-efficiency policy opportunities for electric motor-driven systems. International Energy Agency. Energy Effic Ser 2011 (accessed 08.09.13).

[5] Saidur R. A review on electrical motors energy use and energy savings. Renew Sustain Energy Rev 2010;14:877–98.

[6] ABINEE – Brazilian Association of Electrical and Electronics Industries, ⟨http://www.abinee.org.br/informac/arquivos/efienerg.pdf⟩; 2013 [accessed 08.09.13] [Portuguese].

[7] Procelinfo – Brazilian Center of Energy Efficiency Information, ⟨http://www.procelinfo.com.br/main.asp?View=%7B5A08CAF0-06D1-4FFE-B335-95D83F8-DFB98%7D&Team=&params=itemID=%7B726E91D1-882A-47C5-9358-F325-98E99851%7D;&UIPartUID=%7B05734935-6950-4E3F-A182-629352E9EB18%7D⟩; 2013 [accessed 08.09.13] [Portuguese].

[8] European Union, European Commission, Commission Regulation (EC) no. 640/2009 of 22 July 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for electric motors, ⟨http://www.cemep.org/fileadmin/user_upload/Implementing_measure_motor_and_drives.pdf⟩; 2013 [accessed 08.09.13].

[9] USA, United States of America, Energy Policy Act of 1992. ⟨http://thomas.loc.gov/cgi-bin/query/z?c102:H.R.776.ENR⟩; [accessed 08.09.13].

[10] Ni CC. Potential energy savings and reduction of CO_2 emissions through higher efficiency standards for polyphase electric motors in Japan. Energy Policy 2013;52:737–47.

[11] Almeida AT, Fonseca P, Falkner H, Bertoldi P. Market transformation of energy-efficient motor technologies in the EU. Energy Policy 2003;31:563–75.

[12] ELF Almeida. Energy efficiency and the limits of market forces: The example of the electric motor market in France. Energy Policy 1998;26:643–53.

[13] Brazil, Brazilian Ministry of Development, Industry and Commerce, ⟨http://aliceweb2.mdic.gov.br/⟩; 2013 [accessed 08.09.13] [Portuguese].

[14] CEMEP – European Committee of Manufacturers of Electrical Machines and Power Electronics, ⟨http://www.cemep.org/⟩; 2013 [accessed 08.09.13].

[15] IEC – International Electrotechnical Commission, IEC 60034-30 Standard: Rotating electrical machines – Part 30: Efficiency classes of single-speed, three-phase, squirrel cage-induction motors; 2008.

[16] NEMA – National Electrical Manufacturers Association, Motors and Generators MG1 Standard, USA; 2011.

[17] USA, United States of America, Energy Independence and Security Act of 2007, ⟨http://www.gpo.gov/fdsys/pkg/BILLS- 110hr6enr/pdf/BILLS-110hr6enr.pdf⟩ [accessed 08.09.13].

[18] Abdelaziz EA, Saidur R, Mekhilef S. A review on energy saving strategies in industrial sector. Renew Sustain Energy Rev 2011;15:150–68.

[19] Brazil, Decree no 4.508 of December 11; 2002. ⟨http://www.planalto.gov.br/ccivil_03/decreto/2002/D4508.htm⟩ [accessed 08.09.13] [Portuguese].

[20] Brazil, Brazilian Ministry of Energy and Mining, Ministry of Science and Technology and Ministry of Development, Industry and Commerce. Inter-Ministerial Ordinance 553 of December 8; 2005. ⟨http://www.mme.gov.br/mme/galerias/arquivos/conselhos_comite/cgiee/Portaria_Interministerial_nx_553_2005.pdf⟩ [accessed 08.09.13] [Portuguese].

[21] ABNT – Brazilian National Technical Standards Association, NBR 5383 Rotating electrical machines. Part 1: three phase induction motors, 1999.

[22] IEEE – Institute of Electrical and Electronics Engineers, IEEE 112-1991, Standard test procedure for polyphase induction motors and generators; 1991.

[23] IEC – International Electrotechnical Commission, IEC 60034-2-1 Standard: Rotating electrical machines – Part 2-1: Standard methods for determining losses and efficiency from tests (excluding machines for traction vehicles); 2007.

[24] IEEUSP – Institute of Energy and Environment of University of São Paulo, ⟨http://www.iee.usp.br⟩; 2013 [accessed 08.09.13] [Portuguese].

[25] INMETRO – Brazilian National Institute for Metrology, Standardization and Industrial Quality, ⟨http://www.inmetro.gov.br⟩. [accessed 07.21.14].

[26] ISO/IEC – International Organization for Standardization/International Electrotechnical Commission, ISO/IEC 17025:2005 Standard: General requirements for the competence of testing and calibration laboratories; 2007.

[27] ILAC – International Laboratory Accreditation Cooperation, ⟨https://www.ilac.org/home.html⟩ [accessed 07.21.14].

[28] Agamloh EB, Boglietti A, Cavagnino A. The incremental design efficiency improvement of commercially manufactured induction motors. IEEE Trans Ind Appl 2013;49:2496–504.

[29] FJTE Ferreira, de Almeida AT. Induction motor downsizing as a low-cost strategy to save energy. J Clean Prod 2012;24:117–31.

[30] Moses AJ. Energy efficient electrical steels: magnetic performance prediction and optimization. Scr Mater 2012;67:560–5.

[31] MCES Ramos, Tatizawa H, MCG. Ramos. Methodology for the assessment and optimization of induction electric engines aiming to energy conservation in Brazilian industrial sector. Proceedings of The VIII IEEE International Conference on Industry Applications – INDUSCON, Brazil 2008;1:1–6 (Portuguese).

[32] Werner FE, Jaffee RI. Energy-efficient steels for motor laminations. J Mater Eng Perform 1992;1:227–34.

[33] PROCEL – Brazilian National Program of Energy Conservation, BDmotor software, ⟨http://www.procelinfo.com.br/main.asp?View=%7BA6340DFB-8A42-41FC-A79D-B43A839B00E9%7D&Team=&params=itemID=%7BC8833C81-FF1D-45E3-9CF0-D5656CB0DC15%7D;&UIPartUID=%7B05734935-6950-4E3F-A182-629352E9EB18%7D#⟩; 2013 [accessed 08.09.13] [Portuguese].

[34] Thirugnanasambandam M, Hasanuzzaman M, Saidur R, Ali MB, Rajakarunakaran S, Devaraj D, et al. Analysis of electrical motors load factors and energy savings in an Indian cement industry. Energy 2011;36:4307–14.

[35] Al-Ghandoor A. Analysis of Jordan's industrial energy intensity and potential mitigations of energy and GHGs emissions. Renew Sustain Energy Rev 2012;16:4479–90.

[36] ANEEL – Brazilian National Agency of Electrical Energy, Resolution 414 of September 9; 2010, ⟨http://www.aneel.gov.br/cedoc/ren2010414.pdf⟩ [accessed 08.09.13] [Portuguese].

[37] Cao W, Bradley KJ. Assessing the impacts of rewind and repeated rewinds on induction motors: is an opportunity for re-designing the machine being wasted? IEEE Trans Ind Appl 2006;42:958–64.

[38] Prakash V, Baskar S, Sivakumar S, Krishna KS. A novel efficiency improvement measure in three-phase induction motors, its conservation potential and economic analysis. Energy Sustain Dev 2008;12:78–87.

[39] Hasanuzzaman M, Rahim NA, Saidur R, Kazi SN. Energy savings and emissions reductions for rewinding and replacement of industrial motor. Energy 2011;36:233–40.

[40] Cagno E, Worrell E, Trianni A, Pugliese G. A novel approach for barriers to industrial energy efficiency. Renew Sustain Energy Rev 2013;19:290–308.